

# Discharge of the Congo River Estimated from Satellite Measurements

Senior Thesis

Submitted in partial fulfillment of the requirements for the

Bachelor of Science Degree

At The Ohio State University

By

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## **Acknowledgements**

I would like to thank OSU's Climate, Water and Carbon program for their generous support of my research project. I would also like to thank NASA's programs in Terrestrial Hydrology and in Physical Oceanography for support and data.

Without Doug Alsdorf and Michael Durand, this project would have been impossible.

Thank you for all your support and teaching. I also want to appreciate Hahn-Chul Jung and Hyongki Lee for all their help.

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## **Abstract**

The Congo River basin has little in situ data which limits our hydrologic knowledge of the region. Hydrologists using remote sensing data must rely on visible band frequencies or radar technologies (e.g., LandSat and various SAR missions) for measurements of river channel width, length and water surface elevation. Our objective in this study is to determine the discharge of the Congo River and several of its largest tributaries, using only remotely sensed data. Data sets showing where water is found (Global Rainforest Mapping, or GRFM) are combined with data sets showing elevation (Shuttle Radar Topography Mission, or SRTM) to determine the slope of the water. Measuring widths is done with an algorithm or is estimated based on catchment area. We also select a value to express the river channel roughness (Manning's  $n$ ). To calculate slope, we used measured water surface heights (from SRTM) and flow distance values (from GRFM). These variables are combined in Manning's equation to estimate the discharge of the river. We collected a large amount of SRTM elevation data throughout the basin rivers. The Congo mainstem has 159,457 total elevation data points, while some of the major tributaries have between 1,000 and 36,000 points. Slope values were found in linear segments with sharp breaks in between the segments. The river's interaction with topography is clear when the location of the breaks in slope are noted on a map. River slopes in the eastern mountains (part of the high plains surrounding the interior lowlands) range from 31.21 to 135.72 cm/km. Slopes in the interior are low, ranging from 5.39 to 10.79 cm/km.

## Introduction

The amount of water stored and moving through the Congo River Basin is unknown but very important in understanding river ecology, sediment delivery and nutrient transport. The volume and location of surface water is not well studied. Although they are both large tropical basins, there has been much more hydrology research produced for the Amazon River than for the Congo River. A review of the literature suggests that there is about an order of magnitude more published research for the Amazon than the Congo. Many large tropical basins have very little collected data and thus have been studied comparatively less so than basins in developed nations. It is important to global hydrologic knowledge to understand these regions better. Improvements in remote sensing technology are making it possible to study the world with greater precision. It is the goal of this study to focus on one such data poor region, the Congo River Basin, and more accurately estimate the discharge ( $Q$ ) from exclusively remotely sensed data.

The Congo River Basin is a data-poor region as nearly all of the gauging stations are in disrepair and few historic records of depth or channel width exist. Other major rivers have in situ depth and discharge data going back decades, and sometimes over a hundred years (e.g., fishermen, resource management groups and researchers have all collected data). The lack of in-situ data limits validation, which makes the estimation of hydraulic variables in this region especially difficult. The lack of data makes the Congo

River Basin an important area to use remote sensing as the primary data recording method. Our work is among the first to study the hydrology of this region.

## **Study Area**

The Congo Basin is located in Central Africa, spanning nearly the width of the continent (Figure 1). The Congo River originates in the highlands and mountains of the East African Rift system. Lakes Tanganyika and Mweru feed the Lualaba River which becomes the Congo River. The river starts flowing northwards and bends westward and then southwestward as it meets up with its large tributaries from the north. The last 500 km of the river's journey is a series of cataracts and rapids known as Livingstone Falls (one of two locations with the same name) that cut about 300 m (vertically) through canyons to the ocean.

We delineate four basic regions in the Congo Basin. The first region is in the southeast of the basin and has the highest average elevation. This region drains the mountains of East Africa and contains the lakes that initially supply the river. The second region starts where the river comes off the high plains and travels north, then northwest, at a lower elevation. Region 3 begins where the river starts to bend southwest and enters the low-lying wetlands. The river in this area is very wide and the channels are intensely braided. Section 4 is where the river flows from the "bowl" shaped depression of the

basin and cuts deep canyons through coastal mountains to reach the Atlantic Ocean(Figure 3). The river runs relatively straight through this high topography and the narrow channels are reportedly very deep (Dickman 2009).

The Congo River is the only major river to cross the Equator twice. In doing so, the basin lies in both the Northern and Southern Hemispheres such that it receives year-round rainfall from the migration of the Inter-tropical Convergence Zone (ITCZ). After the north has its wet season in the spring and summer, the ITCZ moves south and the remainder of the basin receives large amounts of rain (Seasonal Migration... [updated 2010]). This results in little seasonal variability in the flow of the Congo mainstem.

The Congo Basin crosses several country borders: Democratic Republic of the Congo, Central African Republic, Republic of the Congo, Angola, Zambia, Tanzania, Burundi and Rwanda. Although there are no functioning gauge stations on the Congo, there are about 40 hydroelectric power plants. In 2005, a plan was proposed at a site called Inga Rapids, in the western Democratic Republic of the Congo, to build a dam large enough to provide electricity to the entire African continent (Vasagar 2005) (Figure 2). The project has the potential to produce more than twice the power of the Three Gorges Dam in China (African Dams...[updated 2010]).



## Geology

Made up largely of Mesozoic and Quaternary sediments, the interior of the Congo Basin is nearly surrounded by Precambrian metamorphosed rocks and Proterozoic platform sediments. Limestone, dolomite and phosphate-bearing rocks are widespread throughout which are used by various industries. Mining in the region is predominantly for copper, gold, diamonds and oil. Angola is the second-largest oil producer in sub-Saharan Africa (after Nigeria) and has significant reserves of natural gas. Much of the region's large mineral resource potential remains under-developed due to long-lasting civil wars and a general lack of infrastructure (Rocks ... [updated 2009]).

Analysis of the drainage networks and deltas of Central and East Africa have revealed that the Paleo-Congo may once have flowed east and drained into the Indian Ocean (Stankiewicz 2006). The Rufiji Delta, on the east coast, is over 500 km wide but is the outlet of a relatively small river with a drainage area of 200,000 km<sup>2</sup>. This suggests that a much larger river once had its mouth at the Rufiji Delta. One of the Rufiji tributaries flows through a prominent valley about 50 km wide. It is reasonable to suspect that the headwaters were once much farther west. Two remnant peneplains in the Congo Basin are interpreted as evidence that this basin was tectonically stable on at least two occasions in the past. The lower peneplain is interpreted as the base level of the

drainage pattern that had its outlet in Tanzania, at the present Rufiji River. The Luangwa, today a tributary of the Zambezi river, was a part of this drainage network. This pattern was subsequently disrupted by uplift associated with the East African Rifting in the Oligocene–Eocene (30–40 Ma). The resulting landlocked system was captured in the Miocene (5–15 Ma) by short rivers draining into the Atlantic Ocean, producing the drainage pattern of today's Central Africa.

## **Satellite Data**

This section describes the datasets used in the study, SRTM, HydroSHEDS and GRFM, all with near-global coverage. SRTM data was collected by interferometric synthetic aperture radar (SAR), covering the entire basin. HydroSHEDS is a geo-referenced vector dataset produced from visible band frequencies, i.e., optical imaging like Landsat. GRFM is a radar intensity mosaic of SAR images that fully covers the basin.

### ***SRTM***

The Shuttle Radar Topography Mission (SRTM) was launched by NASA onboard the Space Shuttle Endeavor during an 11-day mission in February of 2000 (Farr et al). The purpose of this shuttle mission was to collect elevation radar data of land to generate the most complete high-resolution digital elevation model (DEM) of the Earth. The

DEM is produced from interferometric processing of the radar phase collected by both of SRTM's two antennas. While land surfaces scatter radar pulses in all directions and thus yield a signal-to-noise ratio (S/N) sufficient for accurate elevation measurements, water surfaces are specular and thus typically yield a low S/N. However, water surface elevation values are available from this dataset because at the short C-band wavelengths used by SRTM, wind roughened water surfaces scatter radar pulses back to the receiving antennae. Essentially, this results in a data set with variable amounts of water surface elevation values, depending on the degree of water surface roughening (Figure 3). The Mission captured data from about 80% of the land surface, between 60° north and 54° south latitude. About half of the land area was mapped at least 3 times to ensure the best possible average. Although 30 meter resolution data is available over the United States, it is not released anywhere else, thus we use data with a 90 meter spatial resolution.

### *HydroSHEDS*

A product based on SRTM data at 15 arc-second resolution, HydroSHEDS (**Hydro**logical data and maps based on **SH**uttle Elevation **D**erivatives at multiple **S**cales) provides geo-referenced vector datasets of river channels (streamlines), watershed boundaries and flow distances (HydroSHEDS 2008). These streamlines were instrumental in the organization of our data for determining important tributaries,

calculating catchment area, quantifying upstream area and determining flow direction. All collected hydrologic data points could be matched with their geographic location on these lines. We used the HydroSHEDS dataset to calculate the drainage area (in km<sup>2</sup>), because the number of grid cells draining to each river segment can be counted in ESRI ArcMap. We checked our numbers against those calculated based on old in-situ data in *Hydrology and Water Resources of Africa* (Shahin 2002) and found similar results.

### **GRFM**

The Global Rainforest Mapping (GRFM) Program is an imaging radar dataset produced by the JERS-1 Synthetic Aperture Radar (SAR) led by the National Space Development Agency of Japan/Earth Observation Research Center (NASDA EORC), in collaboration with the NASA/Jet Propulsion Laboratory (JPL) and other remote sensing research organizations (Rosenqvist 2000). The project goals are to acquire spatially and temporally contiguous L-band SAR data sets over the tropical belt of the Earth. Available pixel sizes for both high- and low-water conditions are: 100m, 500m and 2km. For this research we used 100m mosaics at low-water settings taken from January – March 1996 (Figure 4). Each 100m pixel represents the brightness of the radar reflections. These 8 bit pixels (digital number or DN) are converted to sigma-naught, or the normalized radar cross section, by:  $\text{sigma-naught} = 20 \cdot \log_{10}(6 \cdot \text{DN}_{100\text{m}} + 250) + F$ . The

DN value of each pixel is between 0 and 255 and F is the calibration factor based on the geographic region. The resulting value is in decibels, dB.

A product of this dataset is the water mask, used in both the collection of slope and width data (Figures 5a,b). The rivers are dark because SAR is a side-looking instrument; when imaging water, most of the radiation is reflected away from the radar (“specular reflections”). Pixels were converted from digital numbers into normalized radar cross sections (in units of dB). The GRFM mosaics were filtered two times with a 5 by 5 window median filter to remove speckle noise. The dark areas are presumed to be water due to the nature of radar reflections on open water. Converted sigma-naught values less than -14 dB were categorized as water class (Hess 2003). In the final product, all water pixels had a value of 1 while all other pixels were 0.

## **Methods**

In order to calculate the discharge (Q) of the Congo River and its major tributaries, we use Manning’s Equation, a formula for open channel flow:  $Q = (1/n) * w * z^{5/3} * s^{1/2}$ . The variables needed are Manning’s roughness coefficient (n), channel width (w), hydraulic radius or depth (z) and water surface slope (s).

### *Elevation*

Obtaining elevation values from our datasets requires both SRTM and the GRFM water mask. The SRTM layer provides us with elevation values over the entire Congo River Basin, both land and water. An edited version of the GRFM dataset, the water mask, was created for this and other calculations. The overlay of SRTM and the water mask gave us a dataset that provides water surface elevation values.

### *Slopes*

A straightforward rise-over-run approach yields the slope of the water surface. Plotting flow distances from HydroSHEDS (in km) against elevation values from SRTM (in m) yields river profile figures that show the elevation of each river along its flow path. From these plots we can calculate slope values in cm/km and show where the values change and the locations of major changes in slope.

The Sangha River has a total of 3,989 paired elevation and flow distance points in its river profile plot (Figure 6a). There are two distinct sections that we chose to calculate slope with a linear fit. We selected the regions visually based on an apparent change in grade. The furthest upstream section has a slope of 12.58 cm/km and the longer section that ends at the mainstem Congo has a slope of 10.79 cm/km.

The Ubangi River has 36,709 points and 3 different slope values (Figure 6b). The headwaters have a steep slope of 31.21 cm/km followed by a short and steep section of 70.44 cm/km. The river then has a slope of 8.20 cm/km for about 1,200 km until it meets the Congo River.

The Aruwimi River has only 1,347 points and three different slope values (Figure 6c). The furthest upstream section is 41.63 cm/km, the middle section is 14.30 cm/km and the furthest downstream is 21.76 cm/km.

The Tschuapa River has 2,062 points in its river profile plot (Figure 6d). We did not visually determine any breaks in slope; therefore the river has only one slope value, 8.86 cm/km.

The Kasai River has a total of 6,263 data points and only one slope value for the whole 800 km tributary (Figure 6e). The slope of 14.16 cm/km is relatively steep for the region.

The upstream Congo River has 46,307 data points and 6 distinct slope sections (Figure 6f). The headwaters had a calculated slope of -1.11 cm/km and a large concentration of data points; this indicates a potential error in the SRTM data. Between this upland area and the next reasonable slope value is an area with an estimated slope of 135.72 cm/km

but very sparse data. After this, the slopes that follow are 7.37, 41.62, 8.39 and 18.15 cm/km, with a moderate distribution of points in each section. The second half of the Congo River has a total of 113,150 points with 6 different slope divisions (Figure 6g). The beginning of this downstream section (the middle portion of the mainstem) has a slope of 7.49 cm/km, followed by a section of 5.39 cm/km, together totaling about 1500 km. After this, there are some very steep sections of the river, 55.65, 16.92 and 172.32 cm/km. There are very few data points in the section with the 172.32 cm/km calculated slope, this is likely because the river is in a deep canyon or valley where SRTM radar may not have adequately sampled this reach. The very last portion of the river is a gentle 5.60 cm/km as the river meets the ocean.

### *Width*

We approached the collection of width data in two ways. The first method was with an algorithm developed by Tamlin Pavelsky called RivWidth (Pavelsky 2008). The second technique involved calculating the approximate discharge based on catchment area and using a formula originally from Shahin to estimate width values.

The RivWidth algorithm requires a water mask, i.e., the binary classification of the GRFM dataset, in order to measure widths. The process used to derive the centerline is



based upon techniques of edge detection and boundary definition commonly utilized in computer vision and image-processing applications. The creation of a centerline is necessary because all calculations of the river widths must be made perpendicularly to the direction of flow. The algorithm used to calculate a centerline starts with the binary river mask and determines the distance from each river pixel to the nearest non-river pixel using a uniform-cost search algorithm. The river width is calculated along a series of transects that are orthogonal to the centerline at each pixel along that line. To obtain these orthogonals, the user must input two lengths (segments AB and CD in Figure 7a) from which trigonometric calculations are employed to calculate widths. This technique is effective in both simple and multichannel river systems. In braided rivers or rivers with islands, RivWidth requires two inputs, the channel and river mask, showing individual river channels and river boundaries, respectively (Figure 7b).

The other method we used on two tributaries and the mainstem Congo involves an estimated discharge calculated from catchment area (Figures 9a-d). We used a formula from Shahin 2002 that gives discharge estimates based on drainage area at each point (Figure 8). His formula was made based on catchment area and mean annual discharge (derived from precipitation, P, and evapotranspiration, ET, data) of 33 sub-basins in the Congo Basin. It states:  $Q=0.0119*A^{0.9649}$ . We also used a formula from Moody 2002 which gives width estimates from discharge values, as created from measurements of world

rivers ranging from small, steep mountainous streams to some of the largest alluvial rivers. This formula is:  $W=7.2*Q^{0.5}$ . By combining these formulas and our own catchment area analysis, we created a formula for calculating Congo River widths:

$$W=6.62*Q^{0.61}.$$

### *Manning's n*

We selected one Manning's n value for the entire basin. The value of 0.030 is normal for channels described as 'clean, straight, full stage, no rifts or deep pools' (Chow 1959). It is also a minimal value for both mountain streams with 'bottom: gravels, cobbles and few boulders' and floodplains in 'pasture, no brush' (Figure 10). These parameters seemed to fit the Congo River Basin as a whole with its areas of high elevation, flatter grasslands and inundated floodplains.

### *Depth*

Depth values can be estimated based on width measurements, catchment area or open channel hydraulics power laws. In our preliminary calculations of the Ubangi, Aruwimi and the Congo River mainstem, we calculated channel depth from formulas found in Moody 2002. After calculating widths and discharges based on catchment area, depth approximations could also be found. We used the formula:  $D = 0.27*Q^{0.39}$ . The results can be seen in the discussion section and figures 9a-d.

## Discussion

Our flow distance vs. height plots clearly show breaks in slope and are useful tools to look at water surface elevations in Congo Basin rivers. There are seven plots (each of the five tributaries and the mainstem broken into two halves, Figure 6). They show channel profiles based on water surface elevation values and their associated flow distances. By looking at the DEM and the profiles, we can get an idea of which topographic features in the basin have an impact on the slope of the rivers.

The break in slope on the Sangha appears to occur where the river flows from the higher northern plains to the flatter central depression. The Ubangi River has a steep slope in the headwaters, but for a brief section (no more than 200 km) the slope is extremely high, more than twice the previous value. This could be a region of waterfalls and cataracts as the river leaves the high topographic area. After this, the Ubangi flows at a low 8.20 cm/km in the shallower lowlands of the basin. The Aruwimi River has three breaks in slope, but is always relatively steep when compared to the other tributaries. Even the section with the lowest slope, 21.76 cm/km, is much higher than slope values other rivers have when they meet up with the mainstem. The Tschuapa River, located in the center of the basin, has a slope value which is moderately shallow. The only slope value for the Kasai River is 14.16 cm/km; this is justifiable because the river cuts a very steady path from the moderately high plains of the SW Congo Basin

and into the western depression of the basin. The rate of down-cut must be relatively low in highlands and more severe in the plains to keep the water surface slope so steady.

An interesting observation to take note of is matching break points between tributaries. The rivers in the east all have break points from where they flow off the high plains and into the lower part of the region. For example, the Ubangi and Aruwimi Rivers flow nearly parallel from east to west and have break points at nearly the same location. Further south, the mainstem Congo also has a more significant break point due to the same topographic feature.

The most upstream reach of the Congo River has a negative surface water slope of -1.11 cm/km. This likely indicates that the Congo is wide and behaving more like a lake than a flowing river. The next slope on the Congo mainstem is also unique, mainly because of its magnitude. The 135.72 cm/km section of the river has few data points, which may be a product of how the river cuts into the hillslope and hence the inability of the SRTM radar to image this reach. Because the river cuts from the high uplands to the lower central basin in a short distance, about 300 km, the river has likely carved a deep canyon. This would make it difficult to get many clear data points when viewed from above or at an angle. The rest of the river flows with more moderate slope values as it

moves through the area with a moderate elevation. The second half of the Congo River begins just after the confluence with the Aruwimi tributary and the slopes are consistent with other values for the central lowlands. The last 500 km of the river's course is relatively steep as the river cuts canyons into the mountains on the continent's edge and makes its way to the ocean.

Our plots for the Ubangi, Aruwimi and mainstem Congo River show elevation, slope, depth and discharge. The plots for the Aruwimi River show depth increasing along the course of the river to a maximum depth of about 4 meters. The discharge for this tributary is estimated to be about 1,000 m<sup>3</sup>/s at the mouth (Figure 9a). The Ubangi River shows depths increasing along the flow path and meeting the Congo mainstem at a depth of about 8m. The discharge at this point is nearly 10,000 m<sup>3</sup>/s (Figure 9b). The Congo River has two separate plots for the upstream and downstream halves. The upstream portion shows depths from 5 to 10 meters and discharges of 10,000 m<sup>3</sup>/s (Figure 9c). The downstream half has depths from 6 to 15m and discharge estimates up to 100,000 m<sup>3</sup>/s (Figure 9d).

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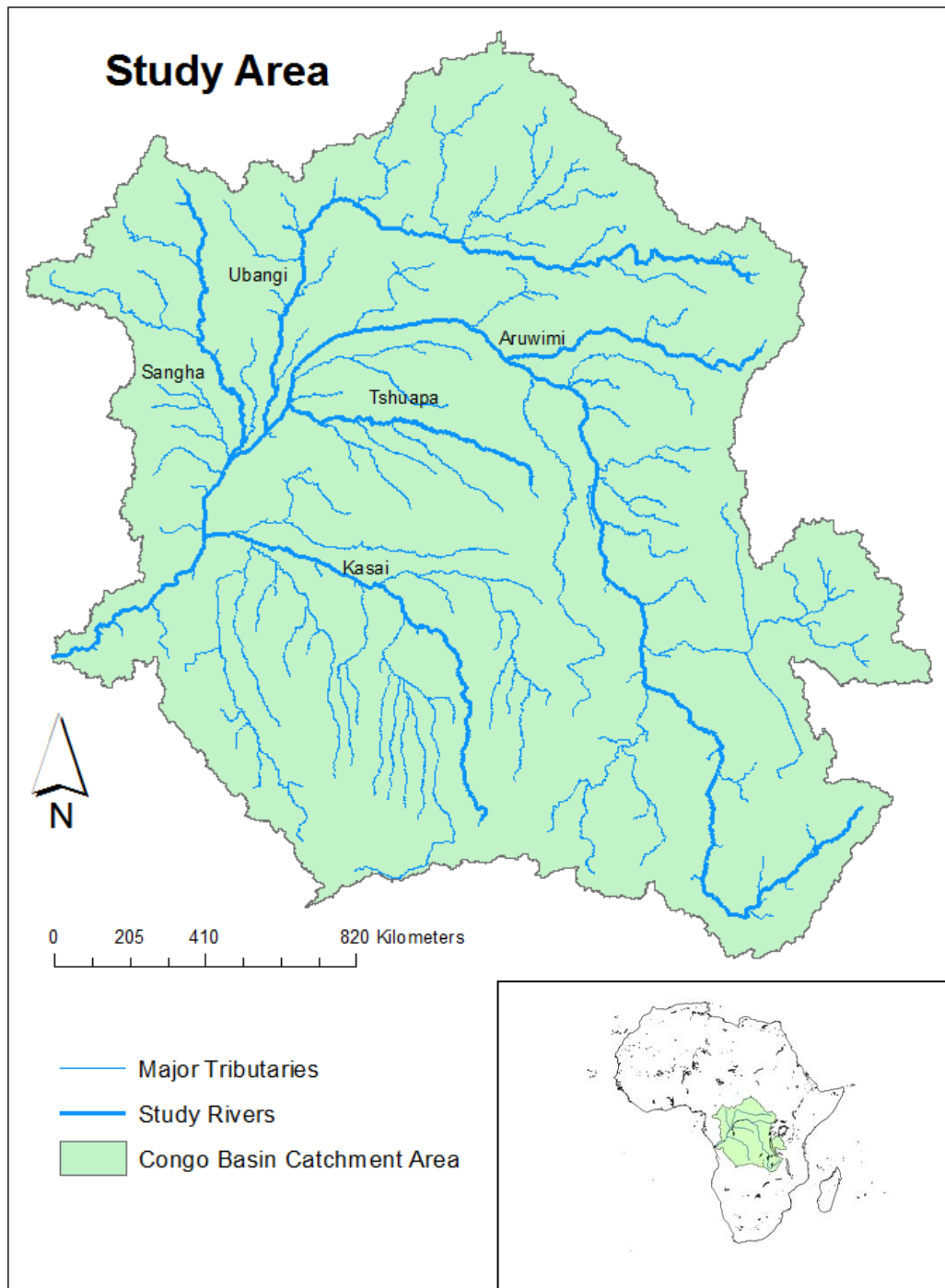
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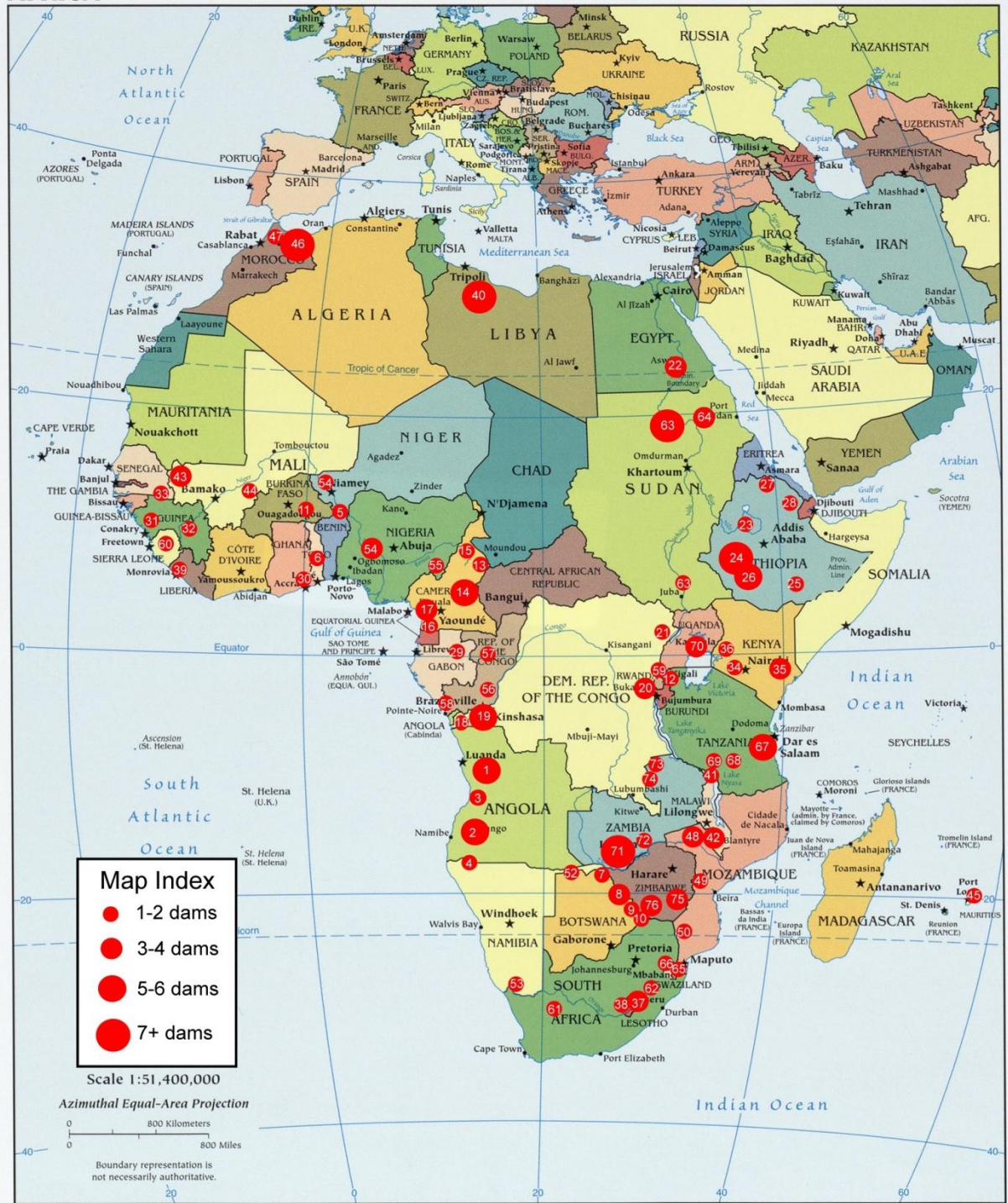
Vasagar, J. 2005. Could a \$50bn plan to tame this mighty river bring electricity to all of Africa?, *Guardian.co.uk*. URL: <http://www.guardian.co.uk/world/2005/feb/25/congo.jeevanvasagar> (cited 25 May 2010).



**Figure 1.** Study area: The Congo River Basin. Shows major tributaries and catchment area boundaries.

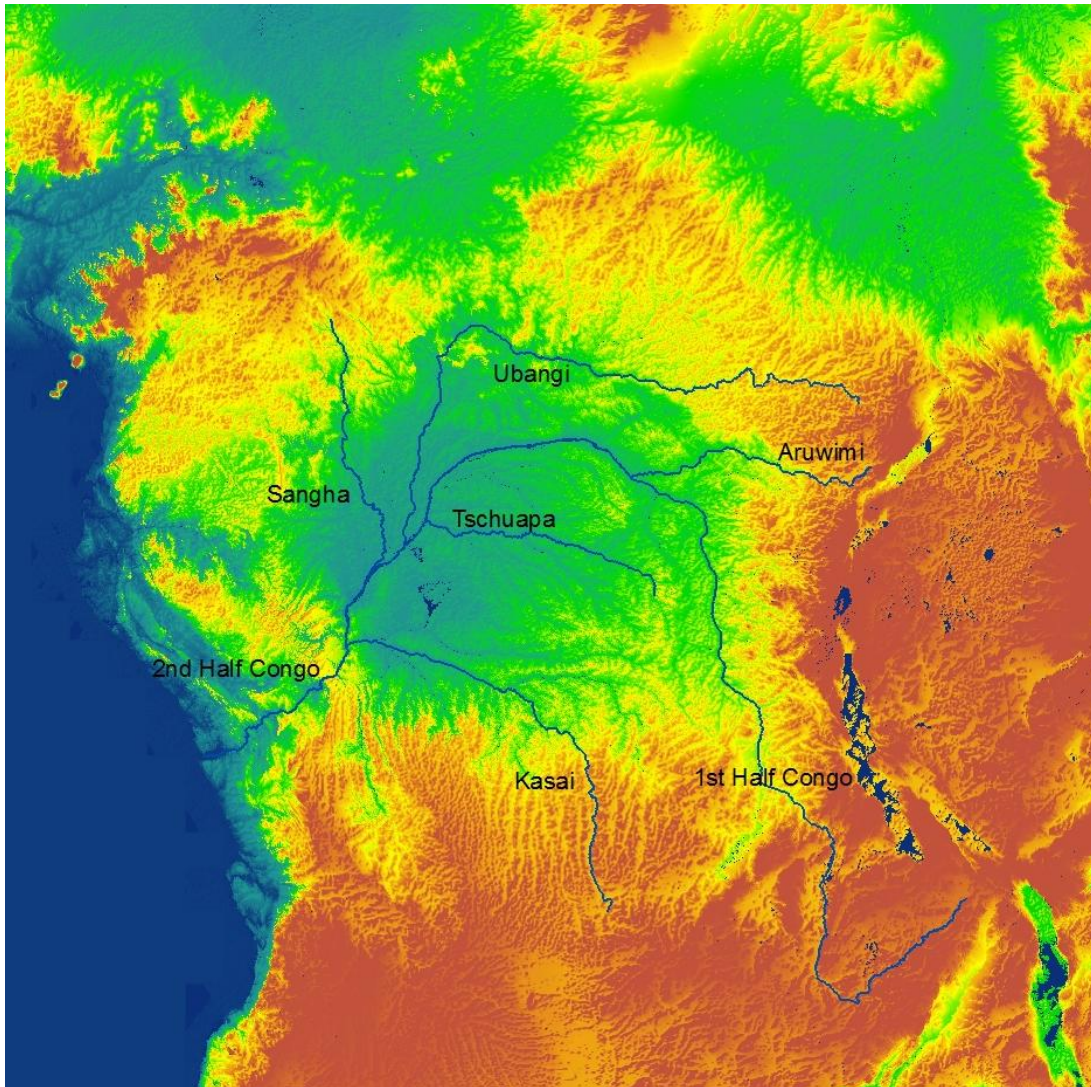


# AFRICA

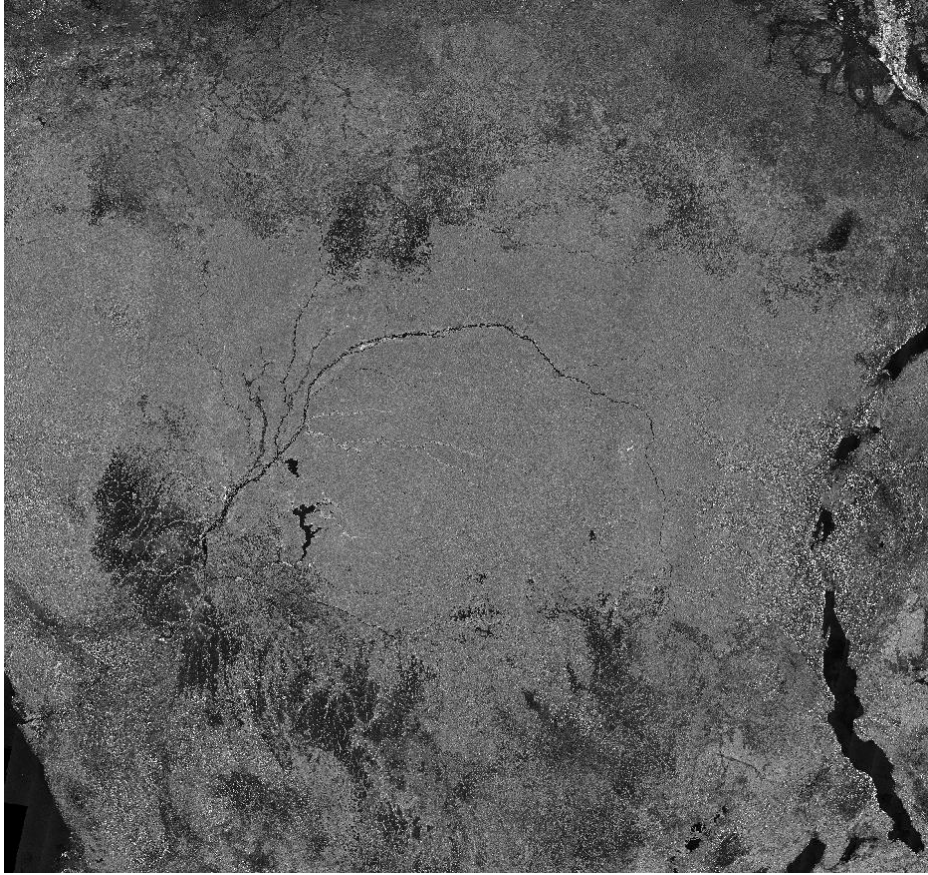


**Figure 2.** Shows proposed dams on African rivers as reported by International Rivers Africa Program, 2010.

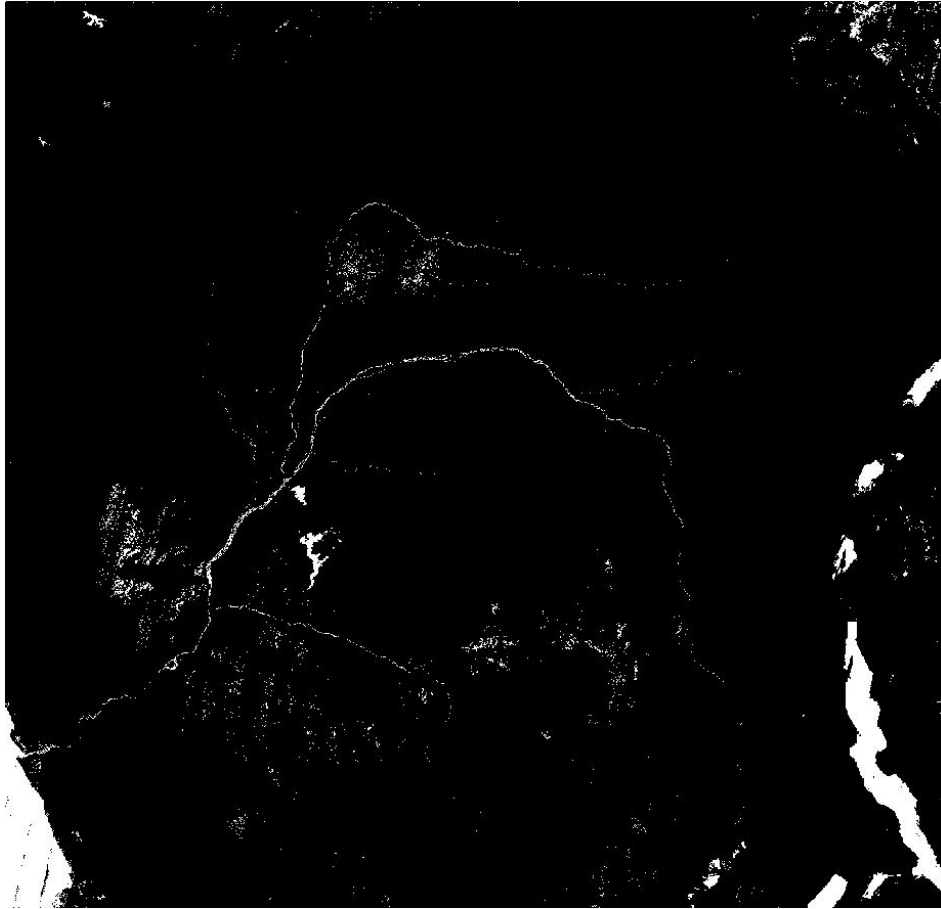




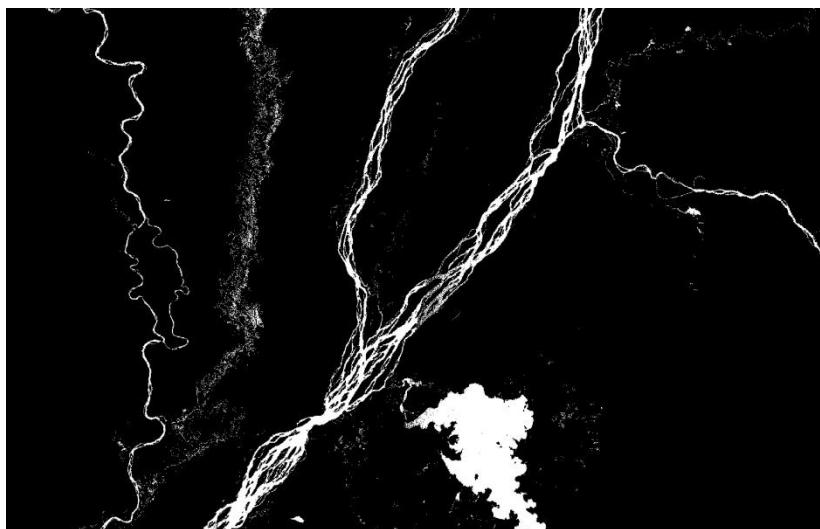
**Figure 3.** Shows the SRTM DEM of the Congo Basin, with streamlines from HydroSHEDS drawn in. Topography can be interpreted from this image and elevation values (in meters above sea level) read for any selected pixel. This image has been edited to appear more 3 dimensional.



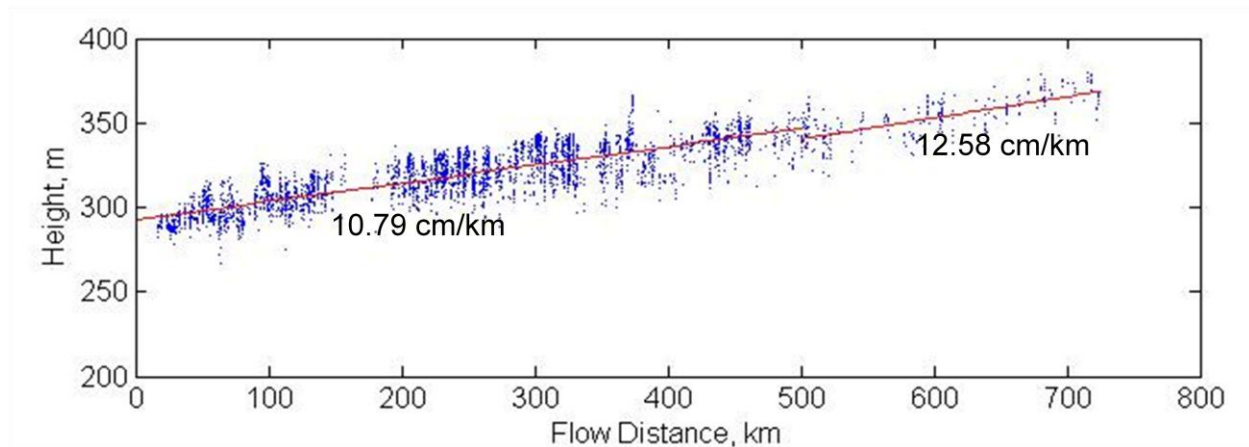
**Figure 4.** GRFM mosaic of the entire Congo River Basin. Each pixel, spaced 100m apart, represents the brightness of the radar reflections.



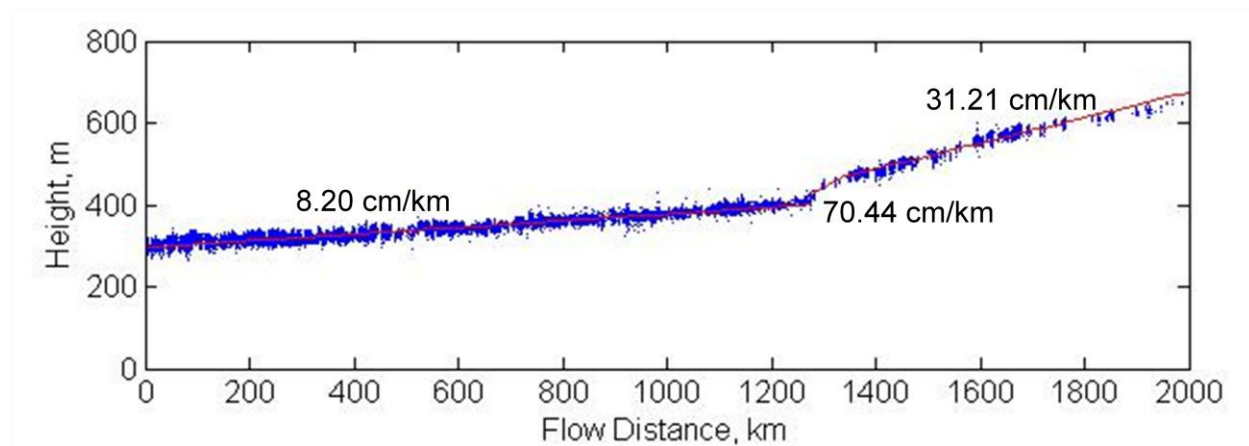
**Figure 5a.** Water mask of the GRFM image. Pixels were converted from digital numbers into normalized radar cross sections (in units of dB). Values less than -14 dB were categorized as water class.



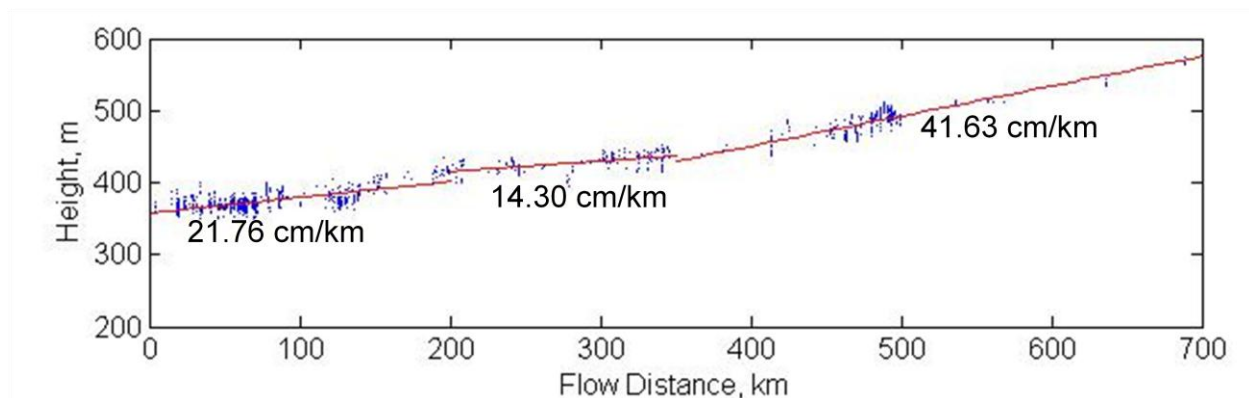
**Figure 5b.** Detail of the water mask.



**Figure 6a.** Elevation and flow distance data from the Sangha River tributary. River shows two distinct slope sections that we calculated with a linear fit. Plot contains 3,989 points.

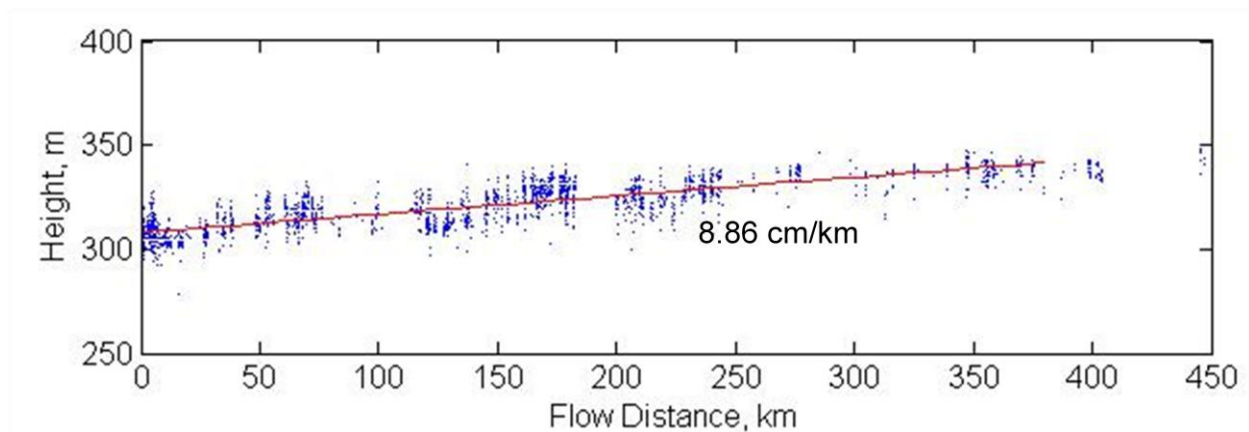


**Figure 6b.** The Ubangi River has 36,709 points and 3 different slope values. Changes in slope match with the regional topography, high plains surrounding the central lowlands.

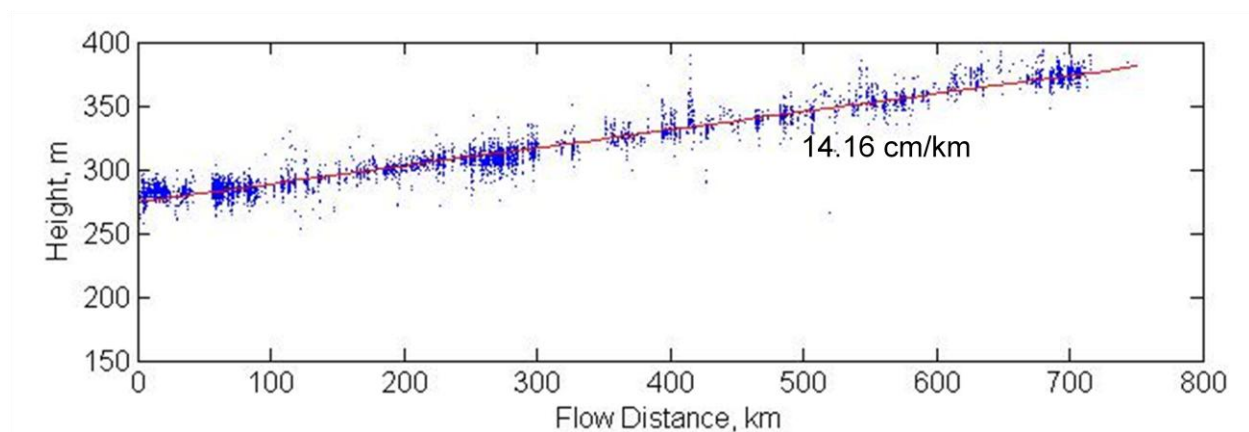


**Figure 6c.** The Aruwimi River has the fewest data points, only 1,347, but has three different slope values. Slope values correspond with flow path from high plains to flat interior.

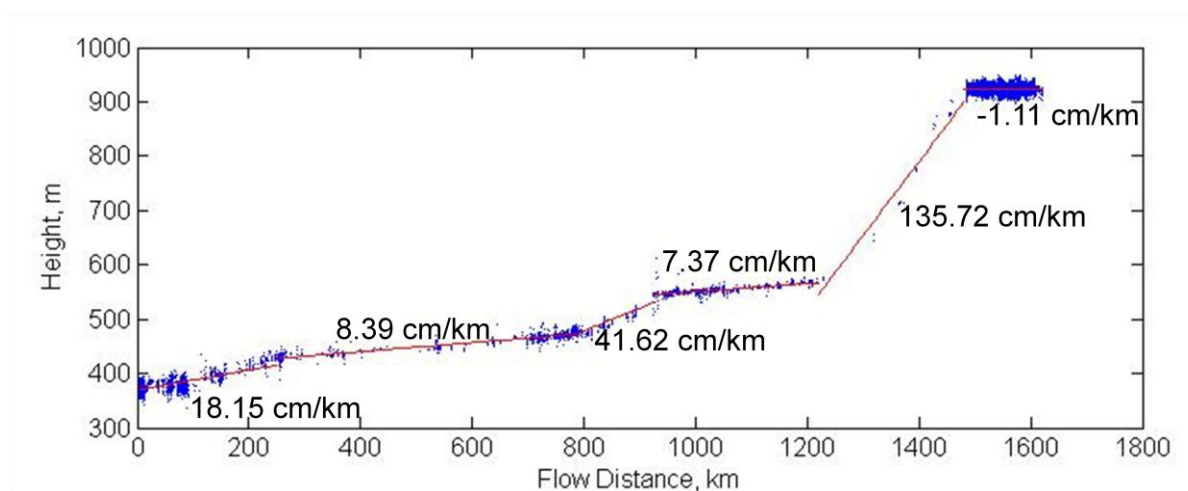




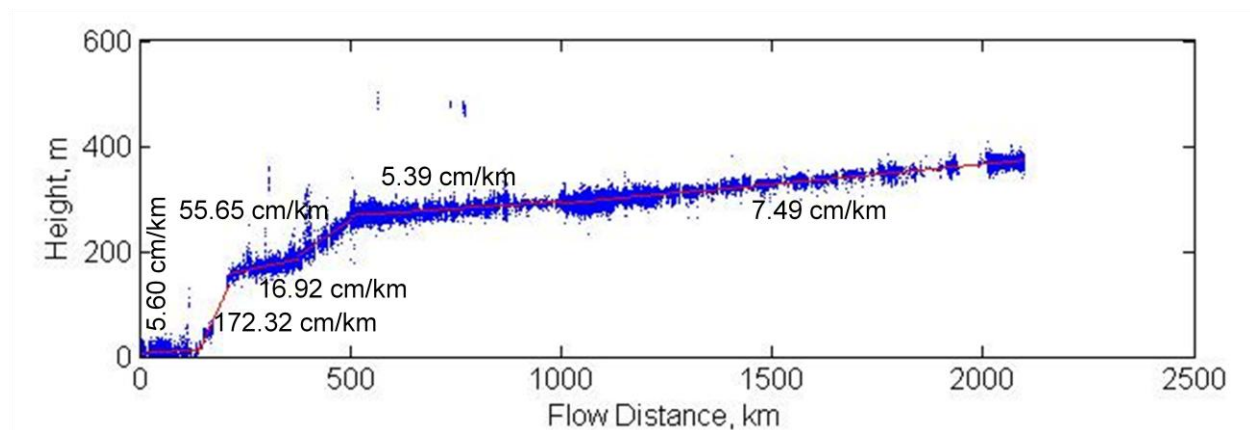
**Figure 6d.** The Tschuapa River, with 2,062 data points, has only one slope value.



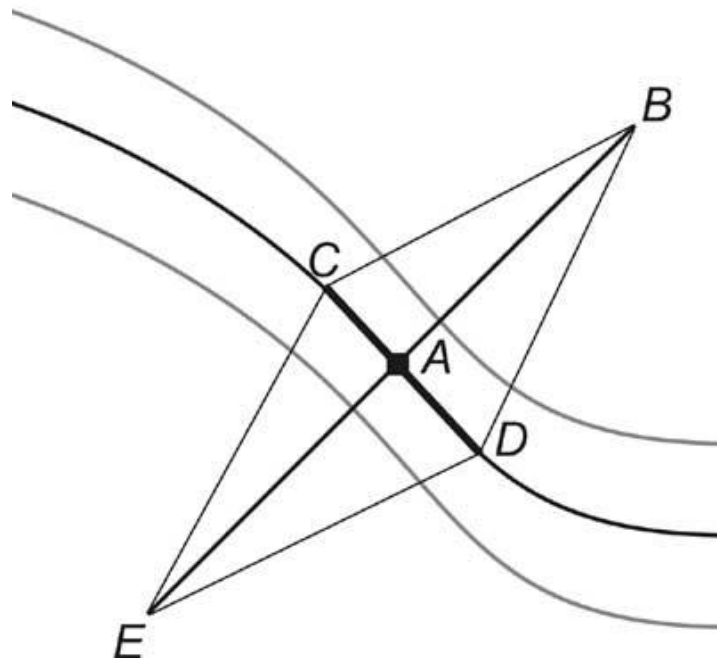
**Figure 6e.** The Kasai River has 6,263 elevation points and only one slope value. The river cuts through the high plains and joins the Congo mainstem in the lowlands.



**Figure 6f.** The upstream half of the Congo River has 46,307 data points and 6 distinct slope sections. The plot clearly shows areas of steep slope in the east and lower slopes to the west.



**Figure 6g.** The downstream half of the Congo River has a total of 113,150 points with 6 different slope divisions. The last 500 km of the Congo's flow is a series of cataracts and rapids that lowers the river's elevation by about 300 m.

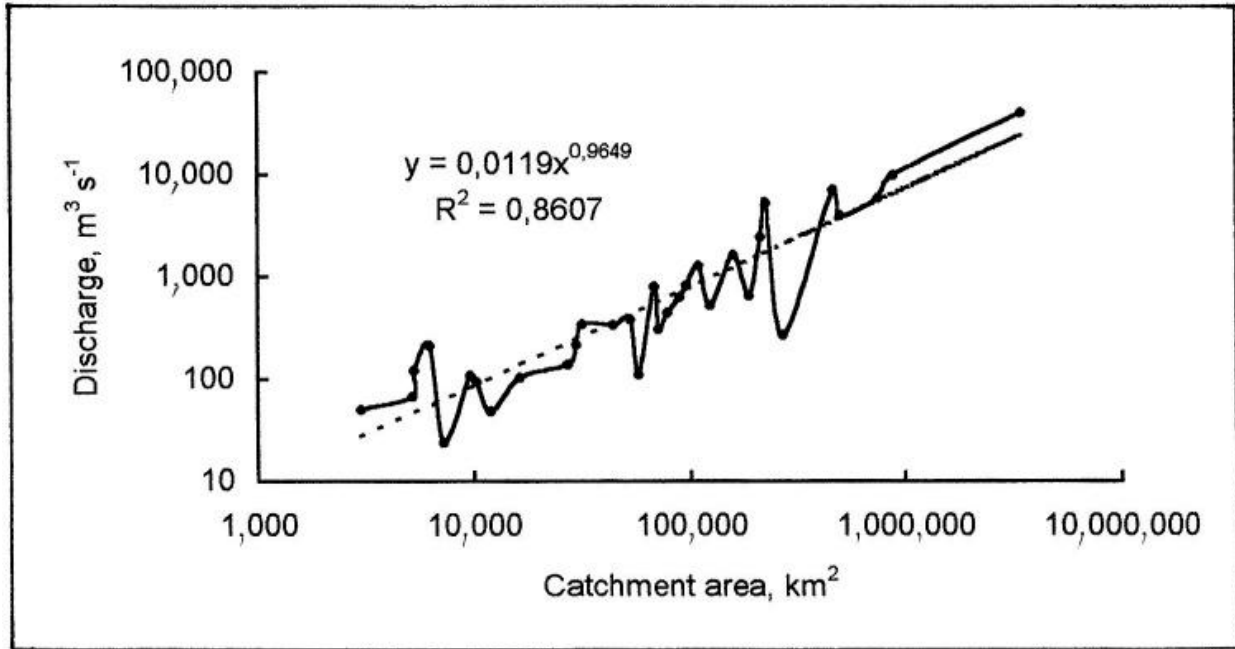


**Figure 7a.** Schematic showing method used to derive an orthogonal to the centerline at pixel A. Segments CD and AE are orthogonal, and the lengths of CD and AB are parameters defined by the user (Pavelsky 2008).

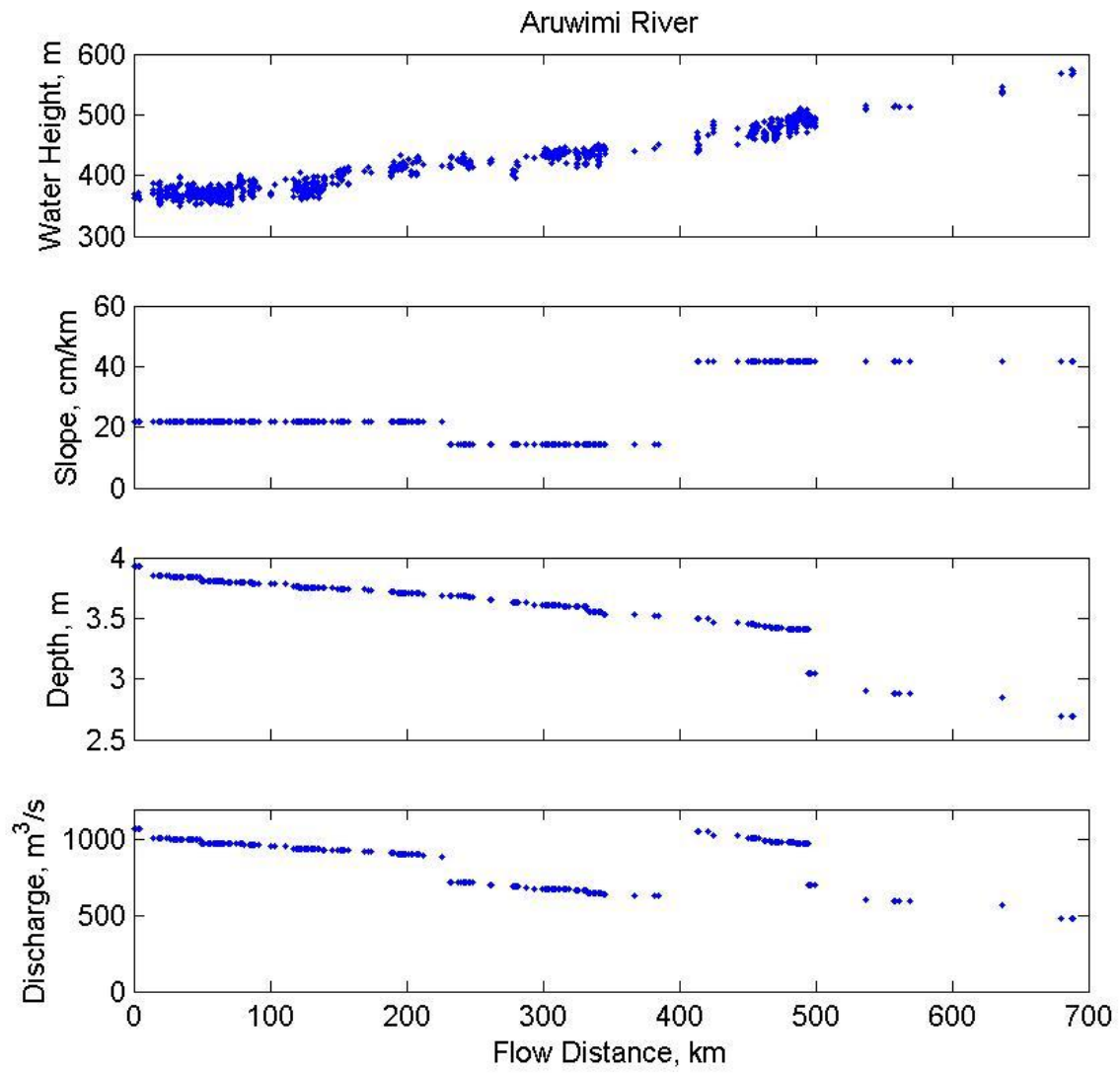


**Figure 7b.** Required RivWidth inputs. Left: channel mask, shows the river's various channels and islands. Right: river mask, shows which pixels lie within the river boundary and which lie outside.

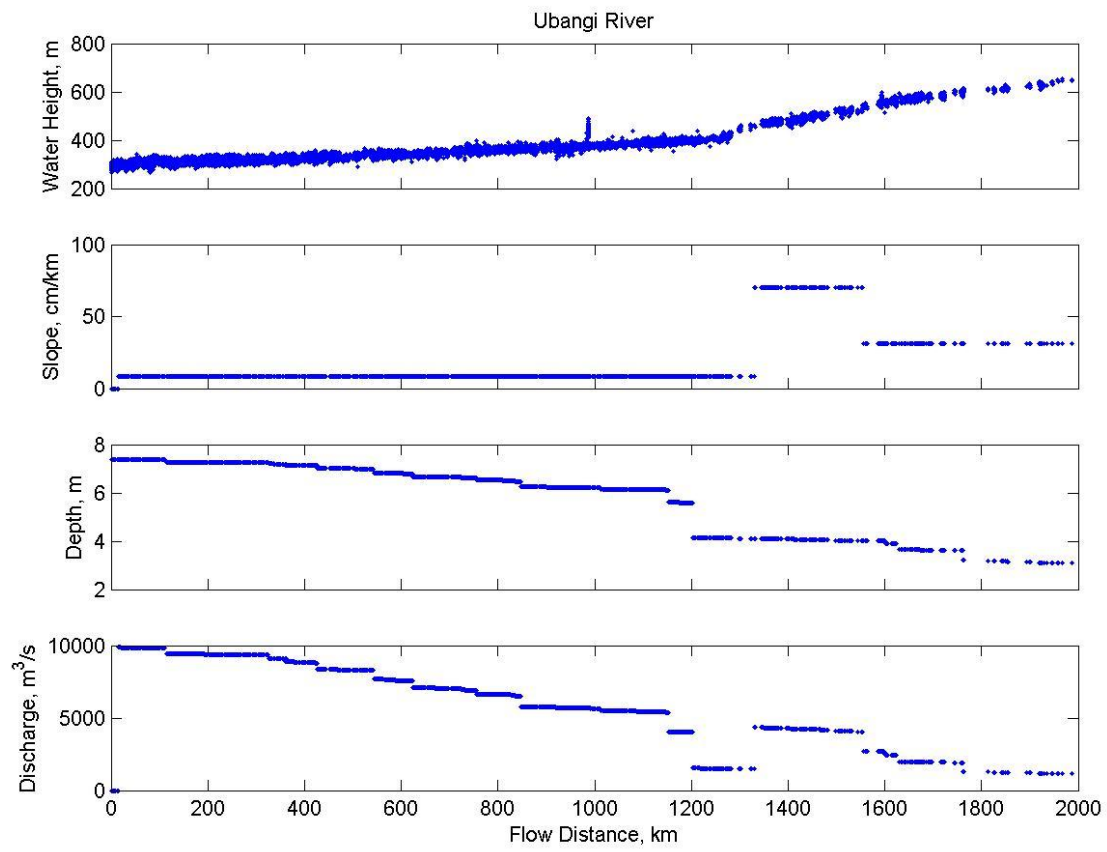




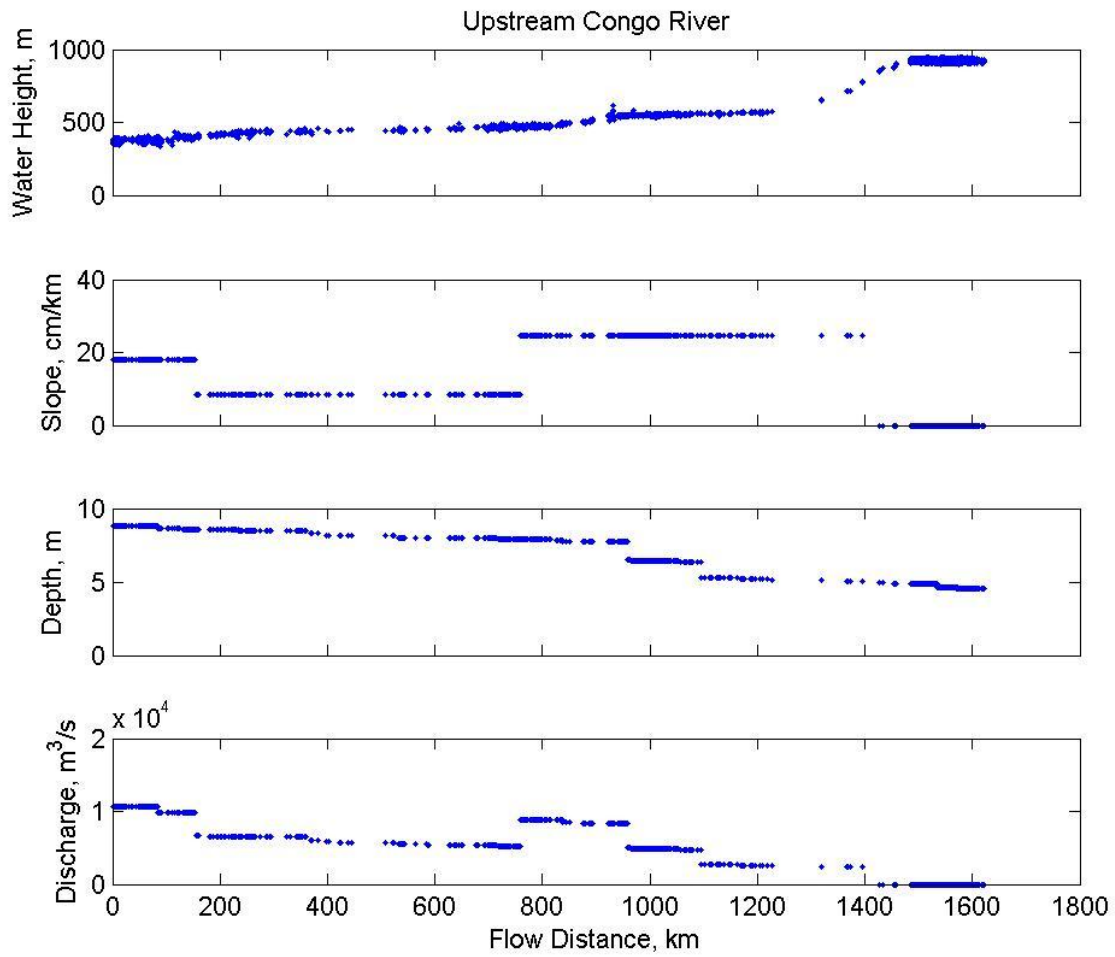
**Figure 8.** Catchment area and discharge relationship as determined from old in situ data from 33 sub-basins of the Congo River Basin (Shahin 2002).



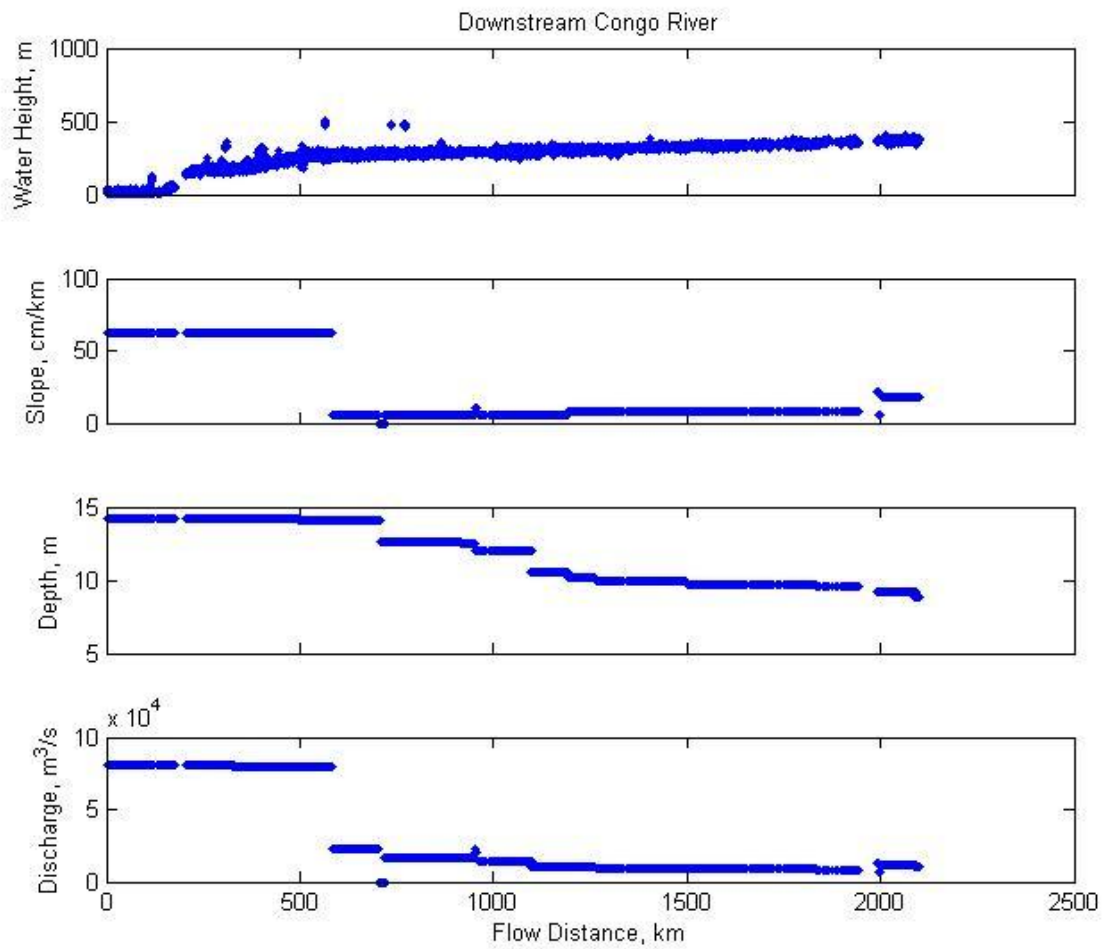
**Figure 9a.** Preliminary depth and discharge values for the Aruwimi River.



**Figure 9b.** Preliminary depth and discharge values for the Ubangi River.



**Figure 9c.** Preliminary depth and discharge values for the upstream half of the Congo mainstem.



**Figure 9d.** Preliminary depth and discharge values for the downstream half of the Congo mainstem.

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
<b>1. Main Channels</b>			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
<b>2. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages</b>			
a. bottom: gravels, cobbles, and few boulders	0.030	0.040	0.050
b. bottom: cobbles with large boulders	0.040	0.050	0.070
<b>3. Floodplains</b>			
a. Pasture, no brush			
1. short grass	0.025	0.030	0.035
2. high grass	0.030	0.035	0.050
b. Cultivated areas			
1. no crop	0.020	0.030	0.040
2. mature row crops	0.025	0.035	0.045
3. mature field crops	0.030	0.040	0.050
c. Brush			
1. scattered brush, heavy weeds	0.035	0.050	0.070
2. light brush and trees, in winter	0.035	0.050	0.060
3. light brush and trees, in summer	0.040	0.060	0.080
4. medium to dense brush, in winter	0.045	0.070	0.110
5. medium to dense brush, in summer	0.070	0.100	0.160

**Figure 10.** Part of the reference tables for Manning's n values for various natural channels (Chow 1959).